Exploitation of Ancillary Service from Energy Storage Systems as Operational Reserve

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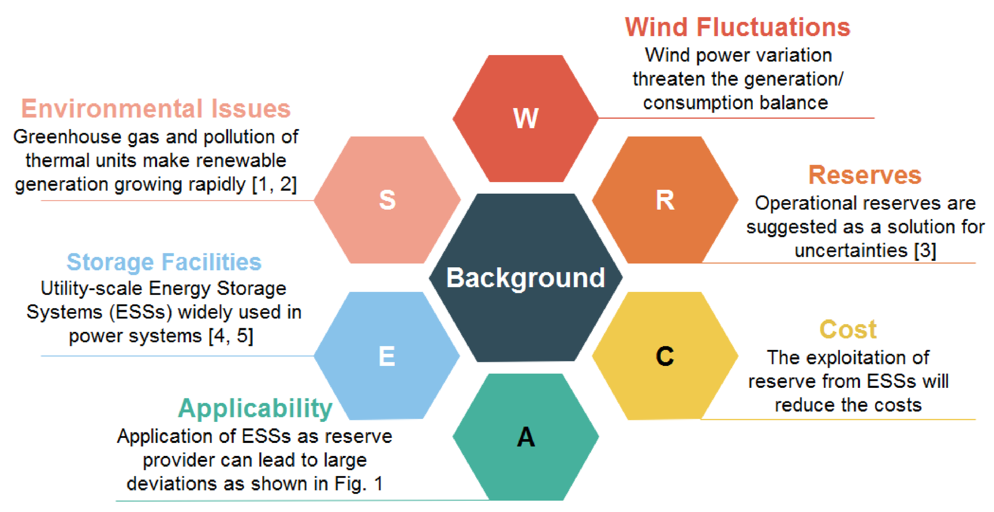
Introduction



Based on the above backgrounds, application of ESSs as a provider of flexibility services is so desirable for system operators. As shown in Fig. 1, this application depends on its sequential dispatches; consequently, the ignorance of such dependency can cause large deviations in the stored energy.

Motivation: The application of ESSs as a service provider is so desirable; however, the uncoordinated application can lead to inseficient energy.

Review: In our previous publication, a coordinated compensation model for ESSs and flexible loads is presented in [4]. The issue of the insufficient reservoir of ESSs in deployments of the reserve is claimed in [6] and [7], while the impact of ESS re-dispatches on stored energy is not reflected in [8] and [9].

Gaps: Few publications properly reflect the issue of large deviations in stored energy of EESs in case of their performance in compensation of uncertainties.

Development of a Stochastic Network-Constrained Unit Commitment (SNC-UC) with these contributions:
- **The reserve cost of ESSs is also carried out as ancillary services.**
- **To consider coordination for reserves deployment of ESSs.**

Model

The proposed SNC-UC consist of three models including generators, ESSs, and wind farms with specified state variables and the main objective function presented by (1).

Storage Devices

Equations	Performance Description
*(2)	The cost function of ESSs including: the cost of discharging at the base schedule and the cost of operational reserves.
(3)	It ensures the ESSs work in one of charging/discharging modes.
*(4), *(5)	They restrict the realizations of reserves in the way that the weighted sum of re-dispatches must be equal to the base schedule.
(7), (8)	They indicate the hourly required upward and downward reserves in charging and discharging modes.
(9), (10)	The hourly limits of charging and discharging are checked by them.
(11)	It regards the dependency of ESS's stored energy between hours.

* The equations (4) and (5) keep the stored energy of ESSs within a range that any large deviations can be offset by intraday decisions, and also (2) considers the corresponding costs as ancillary services.

Wind Farms

Equations	Performance Description
(12)	The objective function contains the cost of wind production and the penalty of wind energy curtailments.
(13)-(15)	The limits of wind poduction and curtailment.
Scenario Generation	The scenarios of wind speed are generated by using the Weibull distribution function. After that, the power production of wind farms is calculated using the generated samples of wind speed and the power curve of wind turbines. Also, the scenario reduction is employed using the SCENRED of GAMS.

Generators

Equations	Performance Description
(16)	The cost function of generators including: the cost of energy and reserves.
(17)-(19)	Calculation of reserves in upward and downward, and the re-dispatches.
(20)	The generation/consumption balance for different scenarios including base case.
Other Eqs	The listed equations are considered as regular constraints.

$$\underset{P_{i/c/w},\, I,\, RG,\, RS}{Min} \sum_t (fG_t + fS_t + fW_t) \quad (1)$$

$$fS_t = \sum_c f(PD^{s_0}_{c,t}) + \sum_c f\begin{pmatrix} RD^+_{c,t}, RC^+_{c,t} \\ , RD^-_{c,t}, RC^-_{c,t}\end{pmatrix} \quad (2)$$

s.t.

$$JC^{s_0}_{c,t} + JD^{s_0}_{c,t} \le 1 \quad (3)$$

$$PC^{s_0}_{c,t} = \sum_s \pi_s PC^s_{c,t} \quad (4)$$

$$PD^{s_0}_{c,t} = \sum_s \pi_s PD^s_{c,t} \quad (5)$$

$$P^s_{c,t} = PD^s_{c,t} - PC^s_{c,t} \quad (6)$$

$$-RC^-_{c,t} \le PC^s_{c,t} - PC^{s_0}_{c,t} \le RC^+_{c,t} \quad (7)$$

$$-RD^-_{c,t} \le PD^s_{c,t} - PD^{s_0}_{c,t} \le RD^+_{c,t} \quad (8)$$

$$PC^{\min}_c \cdot JC^{s_0}_{c,t} \le PC^s_{c,t} \le PC^{\max}_c \cdot JC^{s_0}_{c,t} \quad (9)$$

$$PD^{\min}_c \cdot JD^{s_0}_{c,t} \le PD^s_{c,t} \le PD^{\max}_c \cdot JD^{s_0}_{c,t} \quad (10)$$

$$E^{\min}_c \le E^s_{c,t} = E^{s_0}_{c,(t-1)} + (PD^s_{c,t}) \cdot \xi^{Ch}_c - (PC^s_{c,t}) / \xi^{Dis}_c \le E^{\max}_c \quad (11)$$

$$fW_t = \sum_{s,w} \pi_s f\left(CP^s_{w,t}, P^s_{w,t}\right) \quad (12)$$

s.t.

$$P^s_{w,t} \le W^s_{w,t} \quad (13)$$

$$CP^s_{w,t} = W^s_{w,t} - P^s_{w,t} \quad (14)$$

$$\sum_s \pi_s (CP^s_{w,t}) \le 0.2 \times W^s_{w,t} \quad (15)$$

$$fG_t = \sum_{s,i} \pi_s f(P^s_{i,t}, I_{i,t}) + \sum_i f(R^+_{i,t}, R^-_{i,t}, I_{i,t}) \quad (16)$$

s.t.

$$-R^+_{g,t} \le r^{+,s}_{g,t} \le Ru_g \cdot I_{g,t} \quad (17)$$

$$-R^-_{g,t} \le r^{-,s}_{g,t} \le Rd_g \cdot I_{g,t} \quad (18)$$

$$P^s_{g,t} = P^{s_0}_{g,t} + r^{+,s}_{g,t} - r^{-,s}_{g,t} \quad (19)$$

$$\sum_{l \in \phi(b)} F^{s,n}_{t,l} + \sum_{d \in \Lambda(b)} D^{s_0}_{d,t} = \sum_{g \in \sigma(b)} P^s_{g,t} + \sum_{w \in \xi(b)} P^s_{w,t} + \sum_{c \in \beta(b)} P^s_{c,t} \quad (20)$$

Other Equations:
- Start-up and shut-down.
- Minimum up/down time.
- Ramp up/down equations.
- Generation limits.
- Load flow equation and limits.

Figures & Tables

Table I. SPECIFICATIONS OF TEST CASES

Cases	1-1	1-2	1-3	2-1	2-2	2-3
Wind Penetration	NWP	NWP	NWP	HWP	HWP	HWP
Reserves of ESSs	Yes	No	Yes	Yes	No	Yes
Coordination of ESSs'	No	No	Yes	No	No	Yes

Table II. COMPARISON OF OPERATIONAL COST ($)

Cases	1-1	1-2	1-3	2-1	2-2	2-3
Generation Cost	265011.1	425037.9	419837.5	237661.9	379215.3	373242
Reserve Cost	88661.5	17529	14227.3	84650.7	24893.4	21020.6
Total Cost	353672.6	442566.9	434064.8	322312.6	404108.7	394262.6

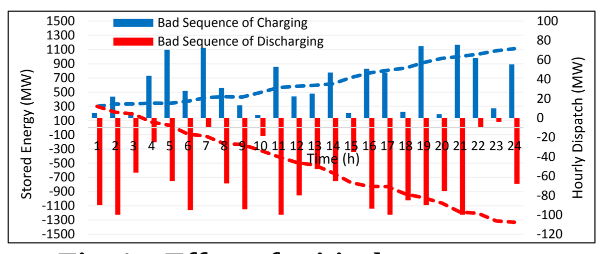


Fig. 1. Effect of critical sequence on ESS's energy.

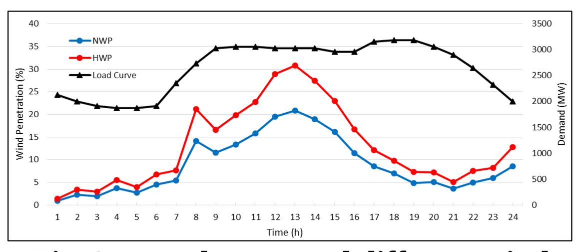


Fig. 2. Load curve and different wind penetrations.

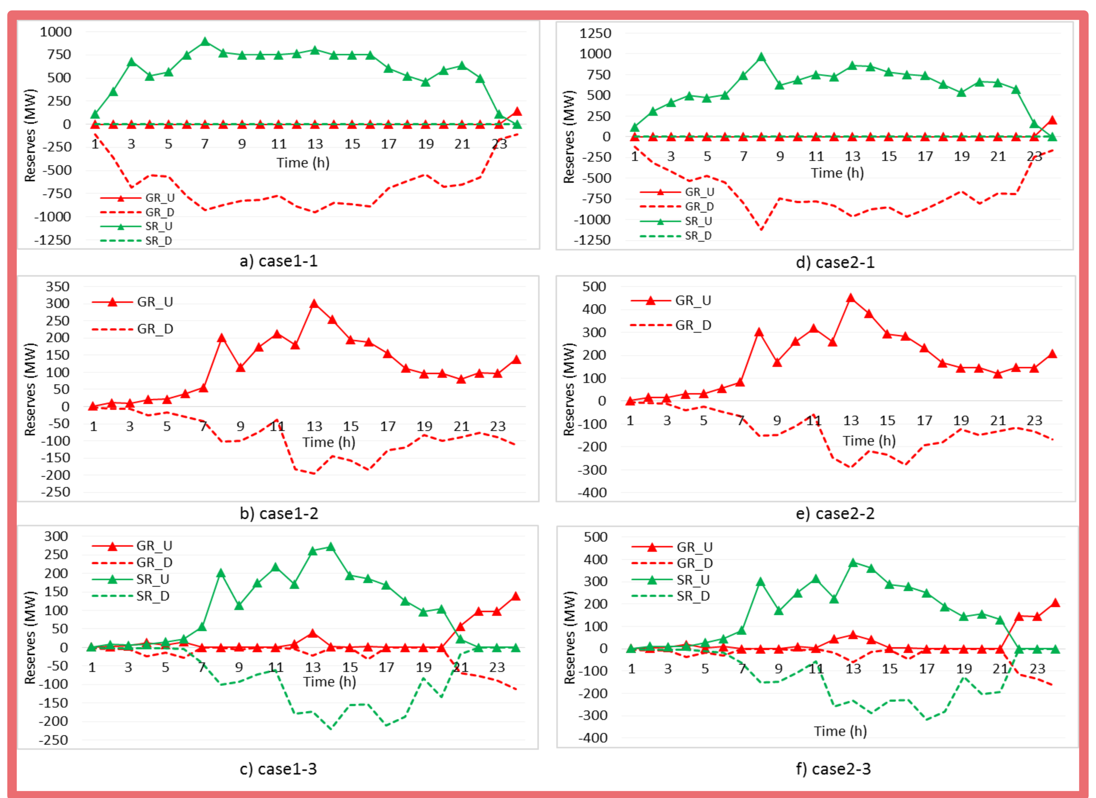


Fig. 3. Hourly reserve deployments in different cases.

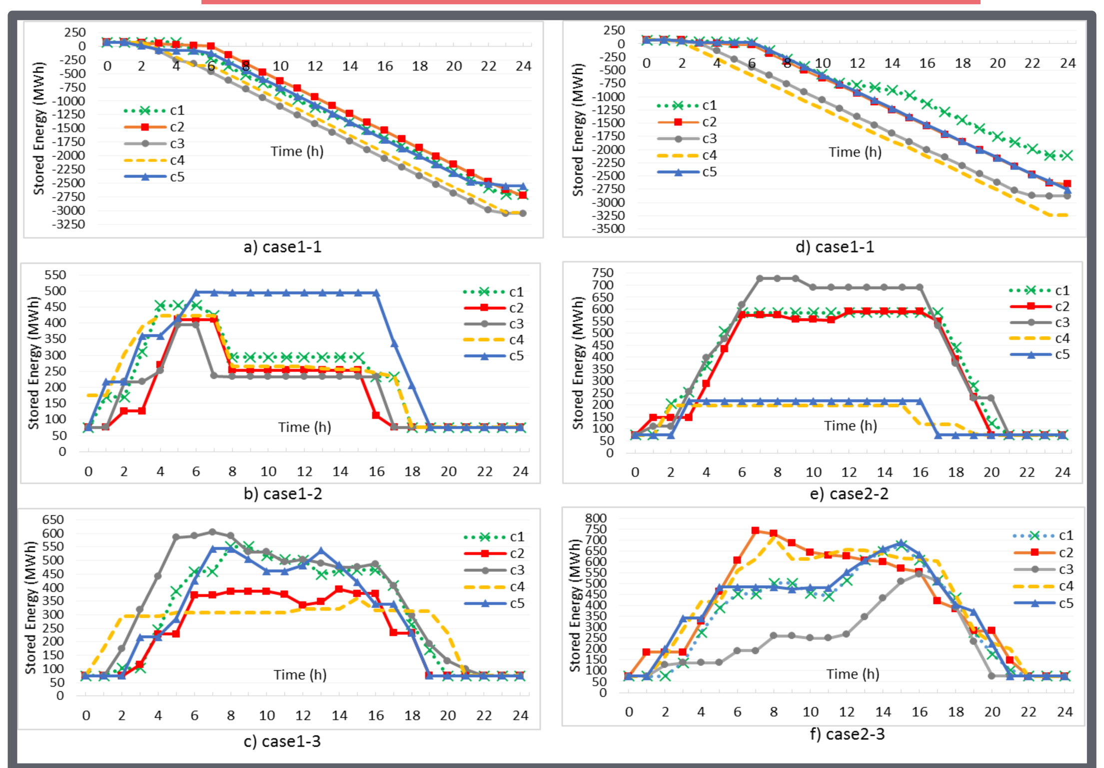


Fig. 4. Expected value of ESSs' stored energy in different cases.

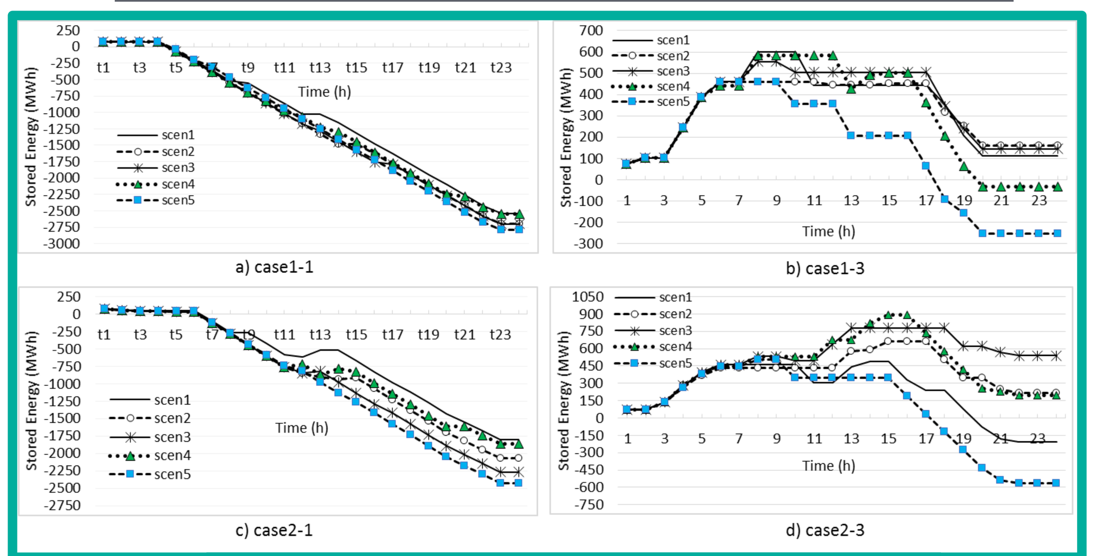


Fig. 5. Stored energy of C1 in different scenarios.

Results

Implementation Data

The proposed SNC-UC model is implemented using CPLEX in general algebraic modeling system (GAMS), on a laptop with Intel i7-core 2.4 GHz and 8 GB of RAM. The RTS-24 test system based on data in [10] is used to evaluate the performance of the proposed model. This test system includes 12 generators, five wind farms, and five ESSs with the capability of deployment regulation reserves. Two levels of Normal Wind Penetration (NWP) and High Wind Penetration (High) are considered to reflect the impact of penetration of wind power on experiment results. The load curve of the test system and hourly wind penetration levels are presented in Fig. 2.

Case Studies

The six cases are defined in Table I based on different conditions of wind penetration, ESSs' participation as a reserve provider, and application of reserve coordination on ESSs. The basic model of all cases is SNC-UC with considering the cost of energy and reserves. These cases are defined to show the performance of various approaches to ESSs' reserve model.

Analysis of Deployed Reserves

The adequate reserve to address wind power fluctuations is displayed in Fig. 3. It can be seen, in Case 1-1 and 2-1, relatively close values are deployed by ESSs in different penetration of wind power. The reason is that the reserve of ESSs is used successively without sufficient reservoir, while the model does not consider any coordination for reserve deployments. This matter is visible in Cases 1-2 and 2-2, which represents a comparison of reserve deployments in without ESS participation. Furthermore, in Cases 1-3 and 2-3, the large share of required upward and downward reserves are deployed by the ESSs.

Analysis of ESSs' Stored Energy

Fig. 4 evaluates the impact of ESSs active compensation on the expected value of hourly stored energy in different cases. It can be seen that in cases 1-1 and 2-1, large deviations occur during the operation period without the use of coordinate ESS compensation. These deviations are up to 3000 MWh and 3250 MWh in cases 1-1 and 2-1, respectively. Cases 1-3 and 2-3 reflect the impact of ESS compensation on their stored energy. These cases can be compared with Cases 1-2 and 2-2; consequently, it reveals the expected value of stored energy does not exceed the limits through the operation period.

ESSs' Stored Energy within Scenarios

For a more detailed analysis of ESSs' energy in different scenarios, Fig. 5 compares cases for C1 (one of ESSs). It can be seen, in both Cases 1-1 and 2-1 the stored energy will be dramatically dropped into large negative values. As shown by (b) and (d), the deviation of stored energy is significantly reduced by applying the proposed coordination. Hence, the remaining deviations can be compensated by appropriate real-time decisions.

Cost Analysis

Table II compares the cost of generation and reserves for different cases. The generation and total costs in Cases 1-1 and 2-1 is significantly lower than Cases1-3 and 2-3, and the reason is that ESSs are discharging amounts of energy in the sequence of hours without the appropriate reservoir. Also, the total cost of Case 2-3 is reduced in comparison to Case 1-3 due to the application more wind energy; however, the reserve cost is increased due to the increased uncertainty.

Conclusions

This paper developed a coordinated model for the exploitation of operational reserves from ESSs to address wind energy fluctuations in an SNC-UC problem. To capture the issue of insufficient reservoir in ESSs' compensation, the model coordinate the values of re-dispatches and the base schedule. Based on the results, the following conclusions are revealed:

- The proposed model successfully deployed the operational reserves from both generators and ESSs, while the expected values of ESS's reservoir are matched to the base schedule.
- The analysis of ESS reservoir in different scenarios shown finite deviations, where they can be captured by real-time decisions.
- Considering the ESS participation in reserve deployments reduced the operational cost by decreasing the need for operational reserves.
- Not-coordinated models resulted in lower cost; however, they lead to the large deviations in the stored energy of ESSs.

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